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Large Diameter, Radiative Extinction Experiments with Decane Droplets in Microgravity

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Introduction

The extinction of a diffusion flame is of fundamental interest in combustion science. Linan [1], Law [2], and Chung and Law [3] analytically and experimentally determined an extinction boundary in terms of droplet diameter and pressure for a single droplet due to Damkohler, or blowoff, extinction. More recently, other researchers [4, 5] demonstrated extinction due to finite rate kinetics in reduced gravity for free droplets of heptane. Chao, et. al [6] modeled the effect of radiative heat loss on a quasi-steady spherically symmetric single droplet burning in the absence of buoyancy. They determined that for increasing droplet diameter, a second limit can be reached such that combustion is no longer possible. This second, larger droplet diameter limit arises due to radiative heat loss, which increases with increasing droplet and flame diameter. This increase in radiative heat loss arises due to an increase in the surface area of the flame. Recently, Marchese *et. al.* [7] modeled fuel droplets with detailed chemistry and radiative effects, and compared the results to other work. The modeling of [7] also showed the importance of radiative loss and radiative extinction.

Experiments by Struk *et. al.* [8] examined the behavior of a large droplet of decane burning in reduced gravity onboard the NASA Lewis DC-9 aircraft, but did not show a radiative extinction boundary due to g -jitter (variations in gravitational level and direction) effects. Dietrich *et. al.* [9] conducted experiments in the reduced gravity environment of the Space Shuttle. This work showed that the extinction diameter of methanol droplets increased when the initial diameter of the droplets was large (in this case, approximately 5 mm). Theoretical results agreed with these experimental results only when the theory included radiative effects. Radiative extinction was experimentally verified by Nayagam *et. al.* [10] in a later Shuttle mission.

The following work focuses on the combustion and extinction of a single fuel droplet. The goal is to experimentally determine a large droplet diameter limit that arises due to radiative heat loss from the flame to the surroundings.

Hardware and Data Analysis

The hardware and equipment supported experiments in a 50 kPa total pressure, reduced O_2 mole fraction (13.5% to 16%), microgravity environment. Partial pressure mixing of air and nitrogen provided the test ambient. All tests were performed in the 5.18 second Zero Gravity Facility at the NASA Lewis Research Center [11]. Two black and white CCD cameras connected to 8mm VCR's recorded the data during the experiment. One camera, backlit by a LED, provided a magnified view of the droplet, and another camera orthogonal to the first recorded the flame view during the test.

An insert to the pressure chamber contained apparatus to deploy, support, and ignite a single n -decane droplet. The insert centered around a 100 mm long, 220 μ m diameter quartz droplet support fiber which has a bead on the end. This bead consisted of either melted quartz 400 μ m in diameter, or a soda lime glass bead 1 mm or 2 mm in diameter, for droplets ranging from 1.7 to 2 mm, 2.3 to 3.1 mm, and 2.7 to 3.5 mm respectively. A 15 μ m silicon carbide (SiC) fiber passed through the fuel droplet, perpendicular to the support fiber. This SiC fiber provided for flame visualization, incandescing where the flame impinged upon the fiber.

A black and white video card transferred images from videotape onto a microcomputer. The computer analyzed a grayscale, eight bit image of the backlight droplet measuring the projected area of the droplet in pixels. Fitting this projected area to the projected area of a sphere gave the droplet diameter. The droplet data analysis proceeded on a field (0.0167 second) rather than frame (0.0333 second) basis, to capture the droplet diameter behavior with improved temporal resolution. The burning rate constant reported in this article was an average over the central region of the droplet diameter history. This central region occurred after ignition and transition to reduced gravity effects died, and prior to flame extinction. The flame data was analyzed by using the Tracker program developed at the NASA Lewis Research Center [12]. The reported flame diameter is the distance between the centers of each glowing region of the SiC fiber. In many of the tests, soot arising due to ignition

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effects obscured the glowing silicon carbide fiber in the early portion of the burn. During these times, no flame diameter is reported.

Results and Discussion

This research showed a number of cases in which the flame extinguished within the five second microgravity time period. In the 14.5% and 15% O_2 mole fraction cases, the results point to two regimes of flame extinction, determined by droplet diameter. For the 15% O_2 cases, one regime exists for 3.04 mm and larger initial droplet diameter, the other for 1.73 mm and smaller initial droplet diameter. The small diameter extinction case in 15% oxygen came from the work of Struk *et. al.* [13]. For the 14.5% O_2 mole fraction cases, results show an extinction regime for 2.92 mm initial droplet diameter and larger, and another for 2.34 mm initial droplet diameter and smaller. Between these two regimes were cases that burned for the entire microgravity time allowed, separating the two flame extinction regimes. These were the only two ambients that showed two extinction regimes. All cases in the 16% O_2 mole fraction burned until impact, with the initial droplet diameter ranging from 2.00 to 3.37 mm. Two tests in a 13.5 and 14% oxygen mole fraction ambient exhibited flame extinction shortly after ignition.

Figure 1 presents a flammability map as a function of droplet diameter and O_2 mole fraction. A filled circle and an X connected by a solid line represent the initial and extinction droplet diameter for a single experiment. The final droplet diameter corresponds with the last measurement of the flame diameter. An open circle and triangle connected by a dashed line represent the initial and final droplet diameters, respectively, for burn to impact cases. The final droplet diameter for these burn to impact cases reports the droplet diameter immediately prior to impact. The letters "A" and "B" indicate two cases with similar initial droplet diameters, the letters used to match the initial and final droplet diameters. The position of a case on this map determined the extinction method for the case, either Damkohler or radiative extinction.

The small droplet diameter region of the extinction curve (Figure 1) represents data consistent with extinction arising due to Damkohler effects [2 - 4]. The extinction droplet diameter increases with decreasing oxygen mole fraction in this region. A second flame extinction region exists for the large droplet diameter, 14.5% and 15% oxygen mole fraction tests. In these ambients the initial and final droplet diameters, for cases showing flame extinction, increased with increasing oxygen mole fraction. Tests in a 16% oxygen mole fraction ambient support this trend; all droplets in these tests burned to impact, even with initial diameter larger than those for which extinction occurred in 15% oxygen mole fraction ambients. The radiative extinction droplet diameter increases with increasing oxygen mole fraction because the higher oxygen concentrations results in an increased reaction rate, offsetting the effects of radiative heat loss.

The region between the Damkohler and radiative extinction regions consists of cases with a flame burning for the entire reduced gravity period. For the 14.5% and 15% O_2 mole fraction cases, the flame diameter exhibited two types of behavior. For the smaller droplets in this region, the flame diameter increased to a maximum then decreased. These results indicate that the flame will not extinguish due to radiative effects in this droplet diameter range, but would have burned to completion or extinguished due to Damkohler effects with a longer experiment time. The second type of behavior includes cases where the flame diameter grew continuously until impact. The eventual outcome of these cases, either radiative or Damkohler extinction, cannot be predicted.

Combined, these two regimes, Damkohler and radiative extinction, form a flammability boundary for single decane droplets in 50 kPa total pressure, with varying oxygen mole fraction ambients. Between these two extinction regions lies an area classified as flammable. A quasi - steady flame should exist within this boundary. The two branches, Damkohler and radiative extinction, meet at a minimum oxygen mole fraction. Based on Figure 1 we estimate this minimum point to be between 14 and 14.5% oxygen mole fraction. Two tests showed ignition and flame extinction outside the proposed flammability limit. For these two tests the burning was a result of ignition transients.

Figure 2 shows the flame diameter as a function of time for four test cases in a 15% oxygen mole fraction ambient, each with different initial droplet diameters. These cases include a large droplet diameter extinction case, two cases with the flame burning until impact and a case with the flame consuming the fuel droplet prior to drop rig impact. The flame diameter for the large droplet diameter extinction case ($D_0=3.35$ mm) and the large burn to impact case ($D_0=2.92$ mm) increase continuously until extinction, 3.13 seconds after ignition, or impact, respectively. The rate of increase in the flame diameter decreases with time, noted by the decrease in the slope of the curve. The remaining two cases presented in Figure 2 showed a somewhat different trend. The flame diameter for the small droplet diameter, burn to impact test ($D_0=1.95$ mm) increases, reaches a maximum, then

began decreasing prior to impact. The flame diameter trend for the burn to completion case ($D_0=1.66$ mm) presents similar phenomena. The increase then decrease of the flame diameter seen in these two cases indicates that the transient flame expansion phase is over and the flame diameter is shrinking in response to the shrinking droplet. The burning enters a phase where quasi - steady assumptions may apply, and suggests that these droplets will not go to extinction.

The droplet and flame diameter histories of these tests do not indicate differences between large droplet diameter and small droplet diameter extinction phenomena. Figure 2 shows similar trends in flame diameter between radiative extinction and a case that burned to impact, as well as similarities between a burn to impact and Damkohler extinction case. The droplet diameter histories in both extinction regimes show droplet heating effects. Also, the change in the rate of vaporization of the droplet due to flame extinction arose well after the flame extinguished in both small and large droplet diameter extinction.

The results from this research indicate that the burning rate constant decreases with increasing initial droplet diameter. Avedisian [4] and Marchese *et. al.* [7] also show this trend. Both researchers point out that radiative heat loss effects may lead to this trend. With increasing initial droplet diameter (and corresponding increase in flame diameter), the heat lost through radiation increases. This loss of heat decreases the reaction rate, leading to a decrease in the burning rate constant.

As pointed out by [4, 7], an explanation for the decrease in burning rate with an increase in initial droplet diameter may be radiative heat loss. The radiative heat lost to the surroundings reduces the flame temperature, the heat feedback and thus the vaporization rate. If the flame temperature is reduced enough the chemical reaction rate decreases, leading to flame extinction. The result of this is the radiative flame extinction boundary in Figure 1.

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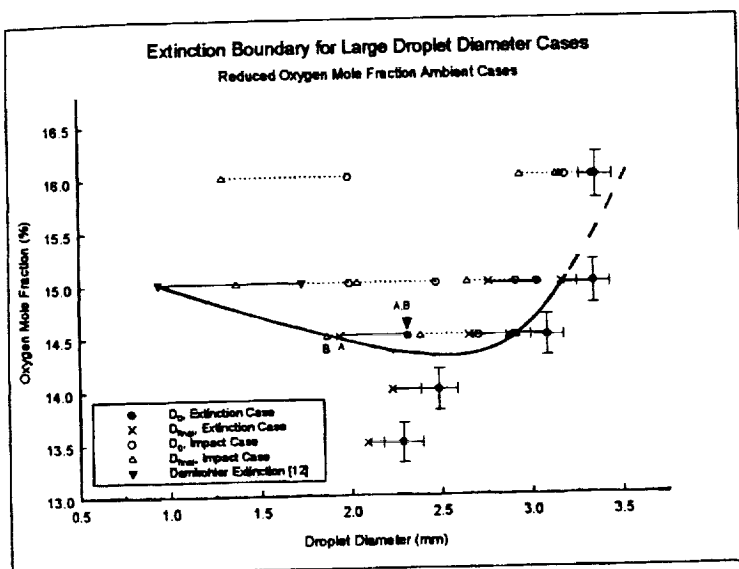


Figure 1. Extinction boundary with both Damkohler and radiative extinction.

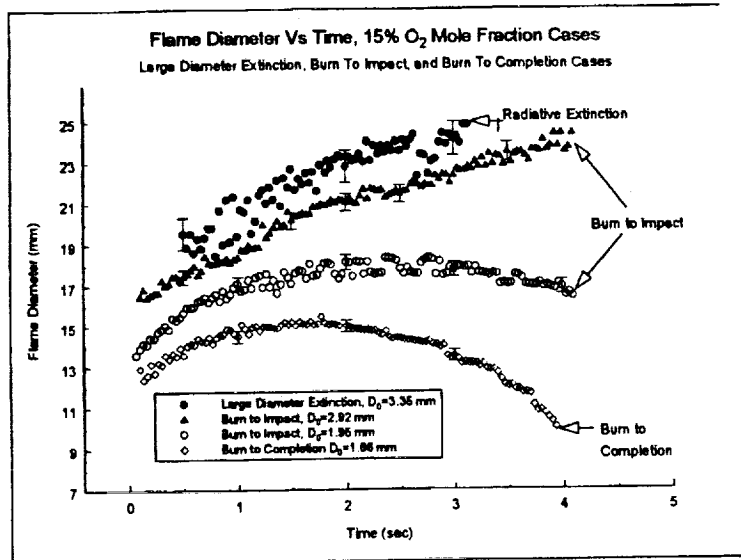


Figure 2. Flame diameter vs time, four tests in a 15% oxygen mole fraction ambient.

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